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Experimental Investigation of the Herschel-Quincke Tube Concept on the Honeywell TFE731-60

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ABSTRACT

This report presents the key results obtained by the Vibration and Acoustics Laboratories at Virginia Tech over the period from January 1999 to December 2000 on the project "***Investigation of an Adaptive Herschel-Quincke Tube Concept for the Reduction of Tonal and Broadband Noise From Turbofan Engines***" funded by NASA Langley Research Center. The Herschel-Quincke (HQ) tube concept is a developing technique that consists of installing circumferential arrays of HQ tubes around the inlet of a turbofan engine. This research is a continuation of previous efforts in which the HQ concept was preliminarily validated on the JT15D engine [1].

This final project report is organized in three separate reports. The research presented in these reports summarizes both analytical and experimental investigations of the HQ concept for reducing turbofan radiated inlet noise. The analytical part of the project involves two different three-dimensional modeling techniques to provide prediction and design guidelines for the application of the HQ-concept to turbofan engine inlets. First, an infinite-duct model was developed and used to provide insight into the attenuation mechanisms of the HQ systems and design strategies. Second, the NASA-developed TBIEM3D code was modified to allow numerical modeling of HQ systems. This model allows for the investigation of the HQ system when combined within a passive liner. The experimental part of this work includes data for "fixed" HQ tubes on the JT15D engine with different inlet acoustic modal content than previously tested. Experimental results for fixed HQ tubes on a full-scale Honeywell TFE731-60 engine are also presented. Also included here is the first set of results of an experimental investigation into adaptive HQ configuration on the JT15D engine. The parameters of the HQ tubes are changed to optimize the attenuation as the engine speed is changed.

The first report presents the analytical modeling and simulation results. The second report describes the experimental results with both fixed and adaptive HQ-tubes on the JT15D engine. Finally, the third report describes the most important results with fixed tubes on the Honeywell TFE731-60 engine. The three parts of this final report are written such that each part is a complete and separate document that can be reviewed independently of the others.

1. INTRODUCTION

The Herschel-Quincke (HQ) tube concept consists of installing circumferential arrays of HQ tubes around the inlet and/or the by-pass duct of a turbofan engine. The application of HQ tubes to turbofan engine inlet noise is a developing technique originally pioneered at Virginia Tech. The research presented in this report is a continuation of previous efforts in which the HQ concept was preliminarily validated on the JT15D engine [1]. The accomplishments of the previous research efforts are summarized in an earlier report [1]. The main previous achievements include:

- Experimental results on the JT15D engine inlet demonstrated BPF tone power attenuation of up to 8 dB with fixed arrays of HQ tubes.
- The HQ tube concept also provides significant attenuation of the broadband component (~ 3 dB power reduction over 0-3200 Hz band.)
- An initial analytical model was developed to investigate the noise control mechanisms of the HQ tube concept and to guide in the design of experiments.

An overview of the tasks involved in this project is shown in Figure 1.1. The project has analytical and experimental components. The analytical part involves the development of two modeling tools for the HQ-tube concept applied to turbofan engine inlets. The experimental part consists of the validation of the approach in two engines, i.e. Pratt&Whitney JT15D and Honeywell TFE731-60 engines, for various HQ-tube configurations. The main objectives of this continuing research effort are:

- To further develop modeling techniques for the design, prediction, and optimization of the Herschel-Quincke (HQ) tube concept for application to turbofan engine noise.

- To experimentally investigate both fixed and adaptive HQ-systems for useful reduction of turbofan inlet noise with realistic components on a running turbofan engine.

The final report is organized in three parts devoted to the various components of the research endeavor. This report corresponds to ***Part III*** that describes the experimental work performed on the Honeywell TFE731-60 to validate the HQ-concept on a full-scale production turbofan engine. The main objective of this experimental effort was to experimentally investigate the potential of the HQ tube concept for reduction of inlet noise on a ***full-scale production engine*** with actual noise generation mechanisms.

The tests were performed at the Honeywell San Tan acoustic test facility on September 27, 1999 in Phoenix, Arizona. An HQ-inlet system containing two arrays was designed based on information supplied by Honeywell and NASA Glenn research center. The design was focused on obtaining reduction of the BPF tone at approach condition, i.e., 60 % engine power. However, the system was tested over the full range of engine power settings. The arrays were designed by the Vibration and Acoustic Laboratories to attenuate the dominant modes present in the inlet at 60% power. Inlet modal data from an earlier test performed by NASA Glenn was used as input in the design. Honeywell was responsible for the fabrication of the tubes and inlet section, and all tests were performed at the Honeywell test facility in Phoenix, Arizona. The effect of each array individually, and the effect of the two arrays together were evaluated as compared to the hard-wall case. Both far-field and induct data were recorded during the tests. Far-field pressure data was measured by Honeywell while induct data was obtained by NASA Langley.

The experimental setup is described in section 2. The engine characteristics are described and include a comparison to the JT15D engine. The proposed procedure for the design of an inlet HQ-system is presented in section 3 including the predicted noise attenuation of the BPF tone. Section 4 presents the most important experimental results subdivided into assessment of the HQ performance on the BPF tone, discussion the modal inlet data, the effect of the HQ tubes on the combination tones and the broadband HQ effect. Finally, sections 5 and 6 describe the most important conclusions and recommendations for future research, respectively.

ANALYTICAL WORK

VPI Infinite Duct Model

- Extend model.
- Study tone and broadband control.
- Investigate noise control mechanisms.
- Optimization.
- Design experiments.

HQTBIEM3D Model

- Implement HQ-tube modeling to TBIEM3D
- Combined Liner-HQ system.
- Study forward and aft. radiation.
- System optimization.
- Modeling of high-bypass engines.

EXPERIMENTAL WORK

Engine Experiments Fixed Tubes

- JT15D engine 1 and 2 arrays.
  - $m=1$ and $\mu=0,1,2,3$
  - $m=5$ and $\mu=0,1$
- Honeywell TFE731-60 Engine.
  - $m=2,-8,12$ and $\mu=0,\ldots,5$

Engine Experiments Adaptive Tubes

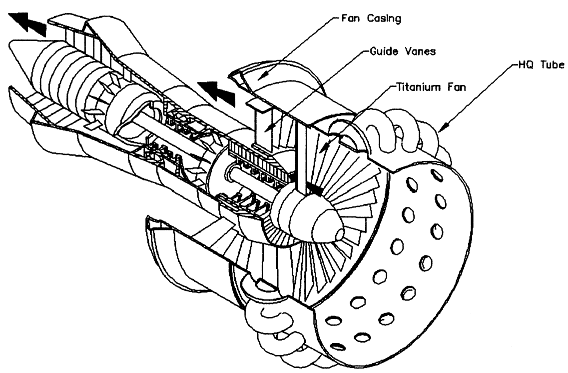
- Investigate tube adaptation mechanisms.
- Evaluate adaptive tubes on JT15D engine.
- Implement adaptive control system.
- Demonstrate adaptive HQ system on JT15D engine.

Figure 1.1: Overview of project tasks.

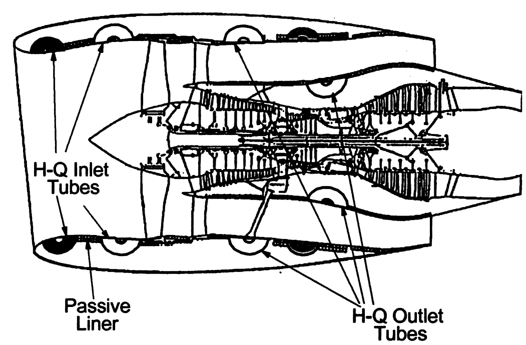
2. EXPERIMENTAL SETUP

The HQ approach to control noise from turbofan engines consists of installing circumferential arrays of Herschel-Quincke (HQ) waveguides in the inlet or bypass of the turbofan engine. A HQ waveguide is essentially a hollow side-tube that travels along (but not necessarily parallel to) the engine axis and attaches to the inlet at each of the two ends of the tube. The HQ concept as applied to a turbofan engine inlet is illustrated in Figure 2.1a where a single circumferential array of HQ-tubes is positioned on the engine inlet. The noise cancellation mechanisms have been recently investigated and they are described in previous reports [1,2].

In general, the HQ concept is envisioned as a viable technique that can be applied to both the inlet and the outlet (i.e., bypass) radiation from a turbofan engine, as shown in Figure 2.1b. Furthermore, as shown in the figure, the HQ tubes will most likely be installed in conjunction with a passive liner. In fact, it is expected that if a the components of a combined HQ-liner system are designed concurrently, the effects of the combined system will supercede the effects of each component individually.



(a)



(b)

Figure 2.1: Schematics of the HQ tube concept (a) on inlet and (b) side view on a turbofan engine implemented on both inlet and bypass ducts.

2.1. The TFE731-60 engine (and comparison to the JT15D)

The engine used for these experiments was a Honeywell TFE731-60 turbofan engine. It is a production turbofan engine with 22 fan blades, 52 exit-guide vanes, and ten struts. The diameter of the inlet at the fan stage location is *0.787 m*. The engine is equipped with an inlet inflow control device (ICD). The purpose of the ICD is to minimize the spurious effects of ground testing on acoustic measurements by breaking up incoming vortices. Experimental results were obtained by operating the engine at the five standard power settings described in Table 2.1. The estimated inlet flow speed is also reported in the table [3].

Table 2.1: Honeywell TFE731-60 Engine test power settings.

Condition	**Speed %**	**Inlet flow speed Mach**
Low Approach	60	0.290
High Approach	67	0.333
Cutback	81	0.430
Take-off	88	0.486
Maximum	98	0.579

At the low approach condition, the BPF tone has a frequency of about 2250 Hz. The HQ system was designed to attenuate the BPF tone at this speed. Knowledge of the acoustic modes present in the engine inlet is necessary for the design of the HQ-waveguides system. A preliminary modal analysis was performed using the engine information. Table 2.2 shows the circumferential order of the modes excited by the rotor-vane and rotor-strut interactions, respectively [4]. Table 2.3 shows the cut-off frequencies for all of the propagating modes in a 0.787 m diameter circular duct calculated for a hard-walled configuration with a flow of 0.29 Mach. All of the modes excited due to the rotor-vane interaction are cut-off at the BPF tone frequency of 2250 Hz. Analysis of the modes excited by the rotor-strut interaction shows that there are three circumferential mode orders excited in the inlet at the BPF. They are the m=2, 12 and –8. This table shows that there are in fact seven modes propagating in the engine inlet at the first BPF at 2250 Hz. They are the (2,0), (2,1), (2,2), (2,3), (8,0), (8,1), and (12,0) modes.

Table 2.2: Mode circumferential order m for rotor-vane and rotor-strut interactions. $m=nB+kV$ where B=22, V=52, n=1,2,3

Rotor-vane interaction				Rotor-strut interaction			
k	**1BPF**	**2BPF**	**3BPF**	**k**	**1BPF**	**2BPF**	**3BPF**
-3	-134	-112	-90	-3	-8	14	36
-2	-82	-60	-38	-2	2	24	46
-1	-30	-8	14	-1	12	34	56
0	22	44	66	0	22	44	66
1	74	96	118	1	32	54	76
2	126	148	170	2	42	64	86
3	178	200	222	3	52	74	96

Table 2.3: Inlet mode cut-on frequencies (Hz). Diameter = 0.787 m, M=0.29.

Circumferential Mode Order m \ Radial Mode Order μ	0	1	2	3	4	5	6	7	8	9	10
0	0.0	527.5	965.7	1400.5	1834.1	2267.3	2700.3	3133.1	3565.8	3998.5	4431.1
1	253.5	733.9	1175.1	1611.4	2046.1	2480.0	2913.4	3346.6	3779.7	4212.6	4645.4
2	420.4	923.1	1372.4	1813.0	2250.4	2686.1	3120.9	3555.1	3989.0	4422.6	4855.9
3	578.3	1103.4	1561.8	2007.8	2448.8	2887.0	3323.7	3759.4	4194.5	4629.0	5063.2
4	732.0	1277.8	1745.8	2197.6	2642.5	3083.7	3522.6	3960.1	4396.6	4832.3	5267.5
5	883.2	1448.1	1925.4	2383.2	2832.4	3276.7	3718.2	4157.6	4595.7	5032.9	5469.2
6	1032.6	1615.4	2101.8	2565.6	3019.1	3466.8	3910.8	4352.4	4792.3	5230.9	5668.6
7	1180.8	1780.2	2275.4	2745.1	3203.0	3654.1	4100.9	4544.8	4986.5	5426.8	5865.8
8	1328.0	1943.1	2446.7	2922.3	3384.6	3839.2	4288.8	4734.9	5178.7	5620.6	6061.1
9	1474.5	2104.3	2616.1	3097.5	3564.1	4022.1	4474.6	4923.1	5368.9	5812.5	6254.5
10	1620.3	2264.2	2783.8	3270.8	3741.8	4203.3	4658.6	5109.6	5557.4	6002.8	6446.3
11	1765.7	2422.8	2950.1	3442.6	3917.8	4382.8	4841.0	5294.4	5744.2	6191.5	6636.6
12	1910.5	2580.4	3115.1	3613.0	4092.4	4560.8	5021.8	5477.7	5929.7	6378.7	6825.5
13	2055.0	2737.1	3278.9	3782.0	4265.6	4737.4	5201.3	5659.6	6113.7	6564.6	7013.1
14	2199.1	2892.9	3441.7	3950.0	4437.7	4912.8	5379.5	5840.2	6296.5	6749.3	7199.4
15	2343.0	3048.0	3603.6	4116.9	4608.6	5087.0	5556.6	6019.7	6478.1	6932.8	7384.5

It is important to compare the parameters of the Honeywell TFE731-60 and the Pratt & Whitney JT15D engines to have a good understanding of their similarities and differences. Figure 2.2 shows a front view of the JT15D and TFE731-60 engines. This figure shows that the TFE731-60 engine has a much modern design of the fan blades than the JT15D engine. In addition, it shows the exciter rods used in the JT15D engine. A comparison of the JT15D and TFE731-60 engine parameters that relate to the BPF tone are shown in the table 2.4. The diameter of the TFE731-60 engine is significantly larger than the JT15D engine, i.e. 0.787 compared to 0.533 m diameter. The BPF tone frequency for both engines is very similar at the design power setting, i.e. 2320 Hz for the JT15D at idle and 2250 Hz for the TFE731-60 at low approach. The main BPF tone noise mechanism in the JT15D is the interaction between the artificially introduced 27 exciter rods and the 28 blades. In the JT15D, the interaction between the rotor and the 33 core vanes is cut-on at the BPF of 2320 Hz. However, experimental work with and without the rods has shown that the rotor-core vane interaction is insignificant compared to the rotor-rod interaction [2]. On the other hand, the BPF tone at 60% power setting is the rotor-strut interaction that is typical of even large turbofan engines. Thus, the BPF tone noise mechanism generation of the TFE731-60 engine is realistic as compared to the JT15D engine. Another important difference between these engines is the realistic inlet flow speed of M=0.29 in the TFE731-60 engine as compared to the ~0.12 on the JT15D engine.

(a) (b)

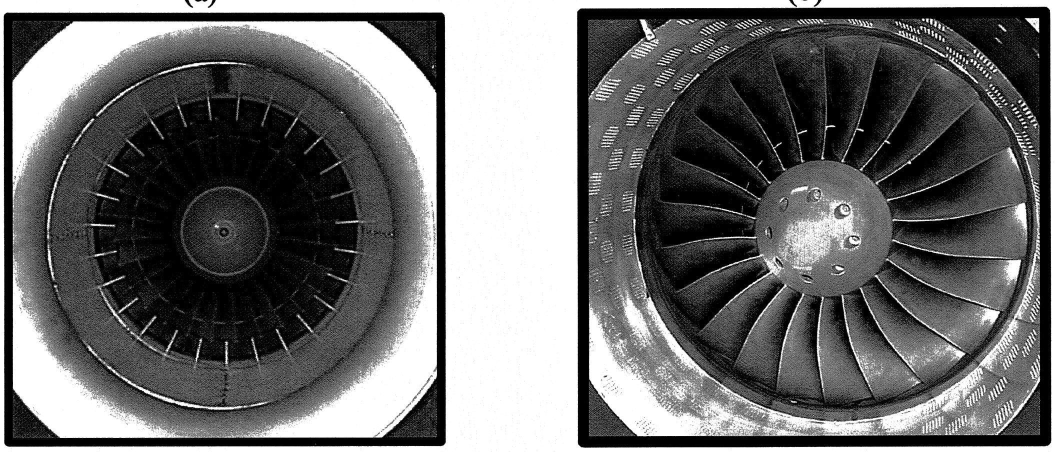


Figure 2.2: Front view of (a) JT15D and (b) TFE731-60 engines.

Table 2.4: TFE731-60 and JT15D engine comparison for BPF tone parameters.

Parameter	JT15D	TFE731-60
Diameter (m)	0.533	0.787
# Fan Blades	28	22
Noise Mechanisms	27 (rods) 33 (core vanes)	10 (bypass-struts)
BPF (design speed)	2320 Hz (48%-idle)	2250 Hz (60%-approach)
m-orders excited (interaction)	*m*=1 (fan-rods) *m*=-5 (fan-core)	*m*=2,-8,12 (fan-struts)

A comparison of the broadband noise component parameters of the two engines is described in table 2.5. For the sake of comparing the broadband characteristics of these engines, it was decided to estimate the number of inlet modes that are cut-on at two frequencies. The number of circumferential m-order modes that are cut-on at the design BPF is 10 and 14 for the JT15D and TFE731-60 engines, respectively. By considering the cut-on radial modes, the total number of modes that can propagate at the BPF is 24 and 39, respectively. If the frequency is increased to 3200 Hz, the total number of modes will then increase to 37 and 72, respectively. Thus, the results in table 2.5 show that the TFE731-60 represents a much more complex sound field than the JT15D, with many more modes present in the inlet.

Table 2.5: TFE731-60 and JT15D engine comparison for broadband parameters.

Parameter	JT15D	TFE731-60
Diameter (m)	0.533	0.787
BPF (Hz)	2320	2250
Range of *m*-orders Cut-on at BPF	10	14
Total # modes Cut-on at BPF	24	39
Total # modes cut-on at 3.2 kHz	37	72

3. HQ-SYSTEM DESIGN APPROACH

This section describes the design of the Herschel-Quincke (HQ) tube system for the series of tests conducted on the Honeywell TFE731-60 engine. This is the first design methodology for the HQ-system applied to the inlet of turbofan engines. Though this design approach was used for a hard wall inlet and a low engine power setting, it might serve as a building block to develop design methodologies for more practical situations, i.e. lined inlet and multiple power settings. A system containing two HQ arrays was designed with the goal that the two arrays could be tested first independently and then simultaneously to result in three different HQ-system test configurations. The general design approach was to design an optimum array to attenuate the dominant *m*-order circumferential modes. The second array was then designed to attenuate the next dominant *m*-order circumferential mode.

In order to design the HQ system, the modal amplitudes of the disturbance noise in the inlet are required. The design of an optimal HQ-system depends heavily on knowledge of both the magnitude and phase of these modal amplitudes present in the hard-walled inlet of the engine. Unfortunately, reliable modal amplitude data were not readily available for the TFE731-60 engine. Thus, the design was based on a preliminary set of modal amplitude data obtained from NASA Glenn Research Center for the TFE731-60 [5]. The modal data show significant contribution at the BPF tone due to the m=2, 7, 4, 6, 3, 1, and 12 modes. Due to the unreliability of the data, the amplitudes for the modes that were determined to be excited by the rotor-strut interaction, i.e. m=2, 12, and −8 were used in the design process. The first HQ array was designed to suppress the mode order m=2 while the second array was designed to be optimal for reducing the m=8 modes. The HQ-system performance was then evaluated using all the modes from the NASA Glenn data. The analytical code developed at Virginia Tech was used in the simulation [2].

3.1. HQ-SYSTEM DESIGN APPROACH

The steps in the design procedure are shown in the flow-diagram in Figure 3.1. The steps in the design methodology for the inlet HQ-waveguide system are now described.

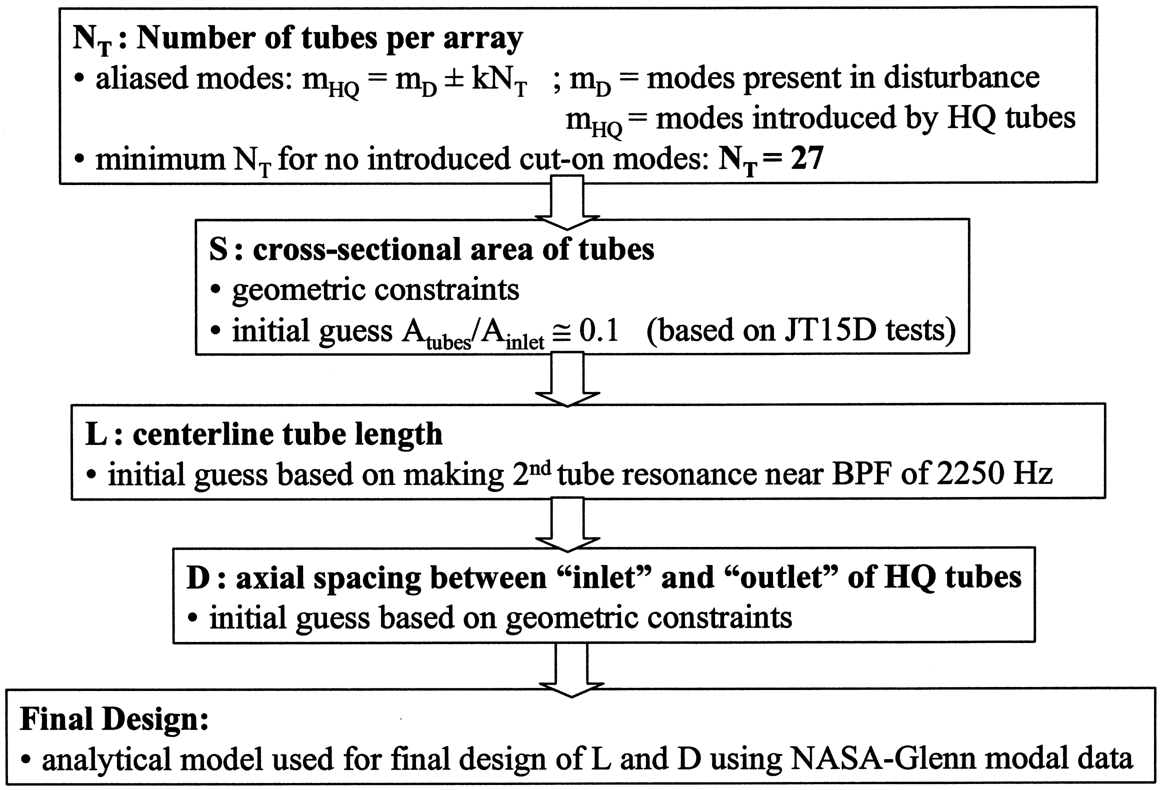


Figure 3.1: HQ-system design procedure flow chart.

1. Number of HQ tubes in array: N_T

The first objective was to determine the number of tubes in the circumferential arrays. Analytical studies have demonstrated that on a hard walled duct the performance of the HQ-system degraded if circumferential scattering was allowed to happen by the HQ-array [2]. Thus, the number of HQ tubes per array, N_T, was designed to be the minimum number that would result in no energy being introduced into propagating (i.e., cut-on) circumferential modes not initially present due to the disturbance fan noise. The modes excited by the HQ-system are given by [2]:

$$m_{HQ} = m_D + kN_T \tag{1}$$

where:

m_{HQ} = circumferential mode order excited by the HQ system,
m_D = circumferential mode order present in the disturbance,

N_T = number of HQ tubes in the array,
k = integer, i.e., $k = \pm 1, \pm 2, \pm 3, \ldots$

The number of tubes was designed to be a minimum with the criteria that the lowest possible m_{HQ} generated by the array would be cut-off. From Table 2.3, the highest m order mode cut-on in the engine at 2250 Hz is $m=14$. Thus, the number of tubes to meet this criterion is $m_{HQ} \geq 15$. To this end, setting $m_{HQ} = 15$, $m_D = 2$, -8, and 12, and $k=\pm 1$ in equation (1) and solving for N_T gives:

- for $m_D = 2$ and
  for $k=1$ leads to $N_T \geq 13$,
  for $k=-1$ leads to $N_T \geq 17$.

- for $m_D = -8$ and
  for $k=1$ leads to $N_T \geq 23$,
  for $k=-1$ leads to $N_T \geq 7$.

- for $m_D = 12$ and
  for $k=1$ leads to $N_T \geq 3$,
  for $k=-1$ leads to $N_T \geq 27$.

From this analysis, the number of tubes in each array is selected as $N_T = 27$. This can be verified by again using equation (1) to determine the m_{HQ} orders excited by the HQ-system with $N_T=27$. The results are shown in table 2.6.

Table 2.6: Circumferential order modes excited by HQ-system m_{HQ} with $N_T=27$ tubes in array at BPF 2250 Hz.

k	$m_D=2$	$m_D=-8$	$m_D=12$
3	-79	-89	-69
2	-52	-62	-42
1	-25	35	15
0	2	-8	12
-1	29	19	39
-2	56	46	66
-3	83	73	93

Assuming evenly spaced tubes, the number of HQ tubes determines the spacing between centers of the tubes around the circumference of the inlet. The center-to-center spacing between adjacent tubes is given as:

$$spacing = \frac{\pi D_{inlet}}{N_T} = 0.0916\, m \;\; (3.61\, in) \qquad (2)$$

or 13.3° in terms of azimuthal spacing.

2. Cross-sectional area of HQ tubes: A_T

The HQ tube cross-sectional area was designed based on the criteria that the ratio of the total tube cross-sectional area to the cross-sectional area of the engine inlet should be ≈ 0.1. This approach was based on the cross-sectional area ratio that produced successful results on the JT15D engine [1,2]. That is,

$$\frac{A_{tubes}}{A_{inlet}} = \frac{N_T A_T}{\frac{\pi}{4} D_{inlet}^2} = 0.1 \tag{2}$$

where A_T is the cross sectional area of a single tube and D_{inlet} is the inlet diameter.

Equation (2) results in $A_T = 0.00180\ m^2\ (2.79\ in^2)$. The equivalent diameter for a circular cross-section of this area is $d_T = 0.0479\ m\ (1.88\ in)$. The first cut-on frequency for a tube of this diameter is 4133 Hz, and is well above the BPF of interest, i.e. there will only be plane waves inside the tubes.

3. Tube Length: L

From previous analysis [1,2], for small area ratios the optimum attenuation of a HQ tube system occurs near the resonance frequencies of the tube assuming pressure release boundary conditions, i.e. the pressure vanished at the the tube's ends $p(0,t)=p(L,t)=0$. In fact, the optimum frequency occurs below the resonance frequencies. The roots of the following transcendental equation give the resonance frequencies of the tube including the mass-like reactive effect of the perforated screen at the tube-inlet interfaces

$$\left\{\left(kL\frac{M_{ps}}{A_{tubes}L\rho}\right)^2 - 1\right\} Sin(kL) = 2kL\frac{M_{ps}}{A_{tubes}L\rho} Cos(kL) \tag{3}$$

where $k=\omega/c$ is the acoustic wavenumber, c is the speed of sound (343 m/s), ρ is the fluid density (1.21 ms^2/m^4), L is the tube length, and M_{ps} is the equivalent mass due to the perforated screen placed at the tube-inlet interfaces. This mass is given by

$$M_{ps} = \frac{A_{tubes}\rho}{100\,\sigma}\left\{t_{ps} + 2a_{orif.}\frac{8}{3\pi}\right\} \tag{4}$$

where t_{ps} is the thickness of the perforated screen, $a_{orif.}$ is the orifice radius, and σ is the screen percentage open area. Once again based on the previous experience on the JT15D engine, the perforated screen parameters selected are given in Table 2.7.

Table 2.7: Perforated Screen parameters.

Thickness t_{ps}	0.76 *mm* (0.03 in)
Orifice radius $a_{orif.}$	0.75 *mm* (0.03 in)
Open area σ	25%

Using the parameters for the perforated screen in equations (4) and (3) results in a tube length of $L=0.145$ *m* that results in the second resonance of the tube to be at the BPF of 2250 Hz, i.e. the 2nd tube's resonance is used to control the BPF tone at 60% power setting. This tube length is then used as an initial guess for the subsequent analysis.

4. Centerline tube length and spacing between inlet and outlet of HQ tubes: *L, D*

The centerline tube length *L*, and interface spacing *D* (see Figure 5) were designed to result in optimal reduction of the modes with a specific *m*-order at the BPF tone. To determine the optimal parameters for the first array of HQ tubes, a parametric study was performed using the infinite-duct analytical model developed at Virginia Tech to predict the reduction for each *m* order present in the disturbance [2]. Again the initial value for the centerline length of the HQ tubes was based on tuning the second resonance of the HQ tube (including the end effects of the perforated screen) to the engine BPF of 2250 Hz. The tube centerline *L* length and interface spacing *D* for each *m* order fan disturbance are shown in Table 2.8:

Table 2.8. Tube length, *L,* and interface distance, *D,* for each dirturbance circumferential mode, m_D.

m_D -order	*L (m)*	*D (m)*
2	0.130	0.090
-8	0.135	0.105
12	0.130	0.12

The parameters of the first HQ-array were selected to control the m=2 mode, while the parameters for the second array were selected to control the m=-8 mode. This was based on the assumption that most of the BPF tone power is due to these two circumferential modes.

In addition to the previous study to design the tubes, studies were carried out to determine the effect of the arrays' spacing on the performance. The results show that the two arrays should be well spaced. However, the two arrays were constrained to fit in a single spool piece 12 inches in length. Thus, the two arrays of HQ-tubes were positioned in a staggered pattern.

5. Final HQ System Design Parameters

The parameters for the final design are presented in Table 2.9 and shown in Figure 3.2.

Table 2.9: Final HQ system design parameters,

Parameter	Array 1	Array 2
Number of tubes in array N_T	27	27
Axial Location x_c (m)*	x_{c1}	x_{c2}
Tube length L (m)	0.130	0.135
Tube interface distance D (m)	0.09	0.105
Tube cross sectional area S (m^2)	0.0018	0.0018
Tube diameter d (m)**	0.048	0.048

Notes:

* The axial separation between the two arrays should be the maximum distance physically possible. In the design, it was assumed that both arrays need to fit on an inlet section with an axial length of 0.3 m (12 in), and therefore x_{c1}-x_{c2} = 0.16 m (6.3 in).

** The diameter is based on a circular hole with cross-sectional area *S*.

Because of the limited space in the spool piece, the HQ-arrays were *staggered* with respect to each other, i.e., the second array is rotated circumferentially 6.67° with respect to the first array. This configuration was accounted for in the analytical model predictions.

6. Analytical Predictions of Final Design

The VPI "infinite-duct" analytical model was used to predict the noise reduction based on the NASA-Glenn mode data. Table 2.10 contains the analytically predicted modal powers and the modal power reductions for the first array, the second array, and both arrays combined for each of the m-orders cut-on in the engine inlet.

Table 2.10: Analytically predicted reductions for HQ design.

m-order	Hard-Wall Power (dB)	Reduction Array 1 Alone (dB)	Reduction Array 2 Alone (dB)	Reduction Both Arrays (dB)
-13	**79.0**	**1.2**	**1.4**	**0.3**
-12	**81.3**	**4.5**	**4.2**	**10.2**
-11	**80.9**	**7.4**	**6.3**	**15.9**
-10	**69.2**	**8.1**	**5.8**	**12.1**
-9	**74.8**	**6.9**	**6.0**	**11.6**
-8	**66.6**	**1.7**	**9.8**	**4.9**
-7	**86.3**	**6.0**	**5.1**	**9.2**
-6	**76.2**	**1.1**	**6.2**	**4.9**
-5	**75.5**	**2.8**	**0.8**	**2.8**
-4	**84.7**	**2.0**	**4.8**	**13.1**
-3	**93.4**	**4.7**	**1.5**	**8.2**
-2	**73.3**	**1.7**	**0.4**	**1.7**
-1	**92.1**	**2.1**	**0.3**	**2.2**
0	**94.0**	**1.3**	**0.4**	**2.4**
1	**96.3**	**0.5**	**0.2**	**0.7**
2	**100.0**	**1.4**	**4.6**	**4.4**
3	**96.8**	**2.5**	**1.4**	**1.5**
4	**98.6**	**7.3**	**5.0**	**14.9**
5	**94.7**	**2.3**	**1.2**	**3.9**
6	**97.4**	**2.4**	**3.1**	**5.3**
7	**99.1**	**5.8**	**4.3**	**9.3**
8	**90.7**	**1.5**	**10.0**	**4.7**
9	**79.8**	**6.9**	**6.0**	**11.6**
10	**87.3**	**8.1**	**5.8**	**12.1**
11	**89.1**	**7.4**	**6.3**	**15.9**
12	**95.2**	**4.5**	**4.2**	**10.2**
13	**89.3**	**1.2**	**1.4**	**0.3**
TOTAL	107.6	2.9	2.9	5.2

In addition to the above predictions, the power reductions were computed assuming identical parameters for the two arrays. For the case of the two arrays having the dimensions in the second column of Table 2.9 (i.e. first array of final design), the total power reduction was 5.2 dB. For the case of the two arrays having the dimensions in the third column of Table 2.9 (i.e. second array of final design), the total power reduction was 4.9 dB.

3.2. FABRICATION OF HQ-SYSTEM

The final HQ tubes were constructed using stereolithography. Figure 3.2 shows a picture of the actual tubes and the parameters associated with each tube. The tubes were constructed with great detail and were essentially exactly as designed.

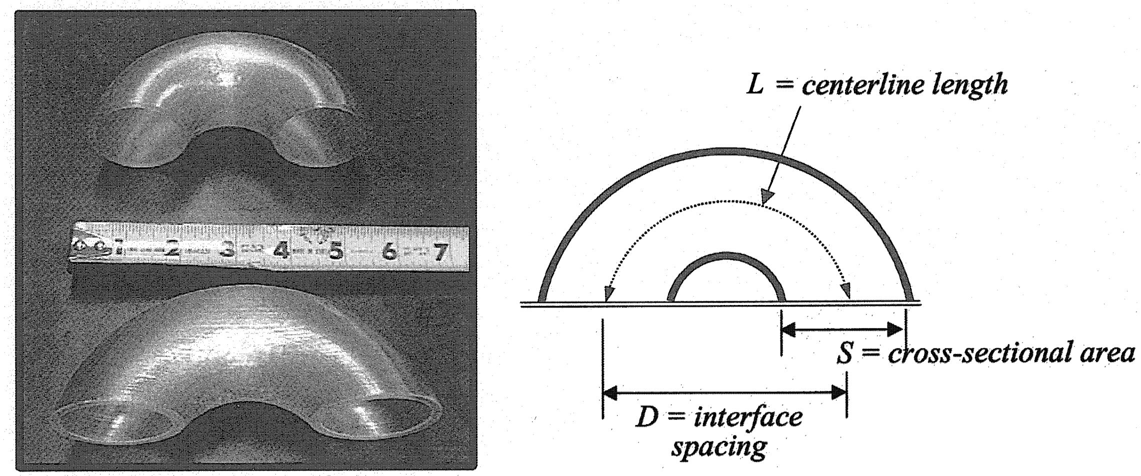
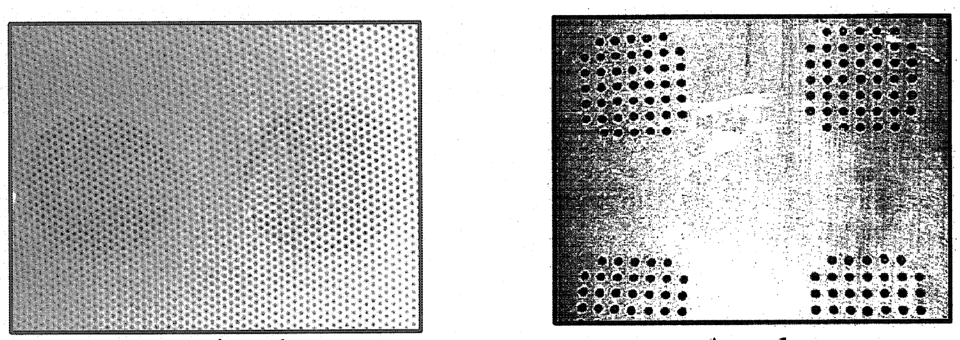


Figure 3.2: Picture of HQ tubes and tube variables.

The actual perforated screen constructed was, however, quite different from the design specifications. Figure 3.3 shows a picture of the designed and actually implemented perforated screens, respectively. In this figure, the pictures are in the same scale for ease of comparison. The parameters of these two screens are presented in Table 2.11. The inlet spool piece with the HQ tubes was in fact a solid cylinder, with small holes drilled in recessed sections where the inlet and outlet of the tubes were connected as shown in Figure 3.4a. The diameter of the holes actually drilled were approximately twice the size of the design specifications, and the thickness of the metal was about twice as thick as well. This resulted in a different percent open area, and a change in the resonance frequencies of the HQ tubes as shown in the table. The shift in the 2nd resonance frequency was approximately 150 Hz, or a 6% decrease. It is believed that the large holes in the constructed screen could have also caused significant flow distortion as will be seen in the experimental results.



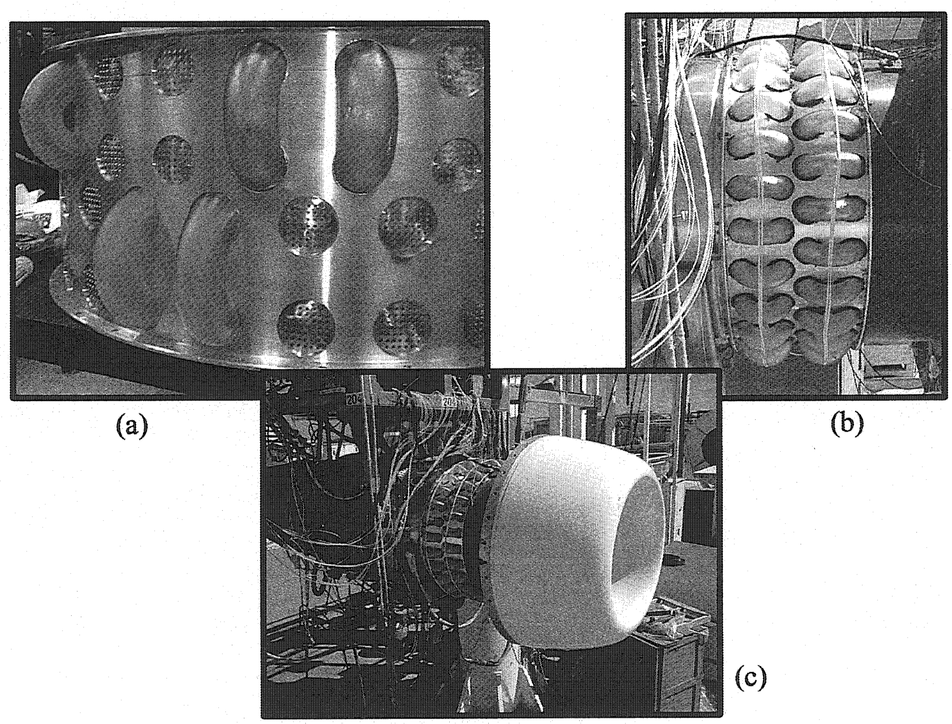
Designed Actual

Figure 3.3: Actual versus designed perforated screen parameters.

Table 2.11: Parameters of actual and designed perforated screens and the predicted tube resonance frequencies.

Parameter	Designed		Actual	
Thickness	0.75 mm (~1/32")		1.5 mm (~1/16")	
Hole diameter	1.5 mm (~1/16")		3.2 mm (~1/8")	
Percentage open area	25%		21%	
Tube Resonance Frequencies (Hz)	Array 1	Array 2	Array 1	Array 2
	1260	1216	1181	1142
	2522	2432	2370	2290
	3784	3650	3569	3448

Figure 3.4 shows several pictures of the HQ-system. Figure 3.4a shows the HQ inlet section with only a few of the HQ tubes attached. The machined recesses where the tubes were attached are clearly shown. The tubes were glued to the inlet section, and then sealed with RTV sealant. Figure 3.4b shows the HQ inlet section mounted on the TFE731-60 engine. Several large rubber-bands were placed around the tubes. Figure 3.4c shows the engine from a front-side perspective. Figure 3.5 shows the complete test inlet with the HQ section installed. Array 1 is closest to the fan, and Array 2 is mounted furthest from the fan. The NASA spool as indicated in the picture was a section in which inlet microphones for the modal inlet data were mounted. The inlet flow control device is not shown in the picture.



(a) (b) (c)

Figure 3.4: Pictures of HQ system, (a) HQ inlet section with partially installed tubes, (b) HQ system section on engine, (c) overall view.

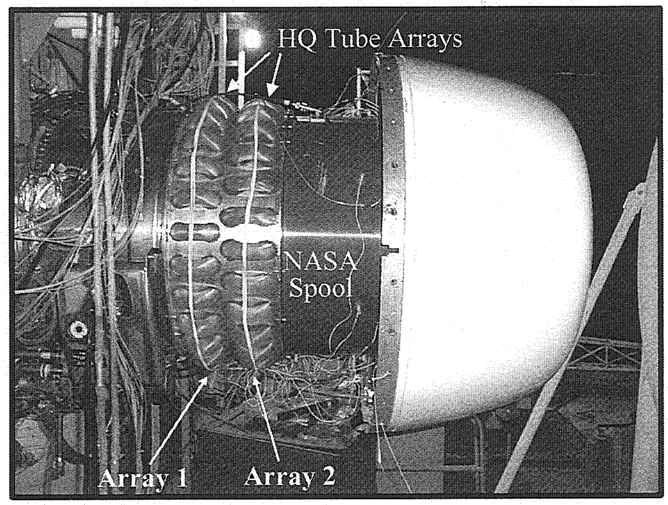


Figure 3.5: Picture of HQ system installed on the TFE731-60.

4. EXPERIMENTAL RESULTS

In this section the key experimental results are presented and discussed. The acoustic field of the TFE731-60 engine was monitored with an array of 32 farfield microphones, spaced along an arc of radius *30.5 m (100 ft)* at 5° increments to obtain the acoustic directivity from 5° to 160° (where 0° is along the engine axis). These microphones were used to evaluate the effects of the HQ tubes on the noise radiated by the engine. It should be noted that some of the microphone data were deemed erroneous due to inconsistent measurements, and in those cases, the questionable microphone data were removed from the analysis. In addition to the far-field data, an array of inlet mounted microphones was used to estimate the duct modal amplitudes. The far-field and in-duct data measurements were responsibility of personnel from Honeywell and NASA Langley Research center, respectively. Additional details of the test setup and procedures are found in a report issued by Honeywell [6]

4.1. RESULTS AT THE BPF TONE

The results at the BPF tone are presented first. Both far-field and induct measured data were analyzed and are presented in this section. The HQ tubes were designed to be effective at a BPF tone of 2250 Hz, corresponding to an engine power setting of 60%.

4.1.1 Far-field Data

In this section, the results presented are from the far-field data. Figures 4.1a show the BPF power reduction for Array #2 over the total sector (0° to 160°) while Figure 4.1b shows the power reduction over two different sideline sectors (50° to 90° and 50° to 130°), for each of the five standard engine speeds tested (60%, 67%, 81%, 88%, and 98%). It is clear that significant reduction of the BPF tone is obtained with Array #2 (furthest from the fan) at engine speeds of 60%, and 81%, with very little reduction at 67%. The power reductions at 60 and 81% are in the range of 2.3 to 4.3 dB. As originally designed, the good performance at 60% is due to the 2nd resonance of the HQ-tubes. It is noted that the BPF at 81% engine speed was 3088 Hz, which was near the 3rd resonance of the HQ tubes as shown in Table 2.11. The attenuation at 81% is most probably due to the 3rd tube's resonance and is a clear indication that the 3rd resonance of the HQ-tube can be used to suppress the BPF tone at higher power settings. This is a new and very significant result, as a test had never before been performed where the BPF was near the 3rd tube resonance. These results suggest that an HQ-tube system can be designed to control the BPF tone at two power settings using two tube's resonances, i.e. the 2nd resonance to control the BPF tone at 60 % and the 3rd resonance to control the BPF tone at 81 %. The poor performance at 67% is because the BPF tone is between the 2nd and 3rd tube's resonances.

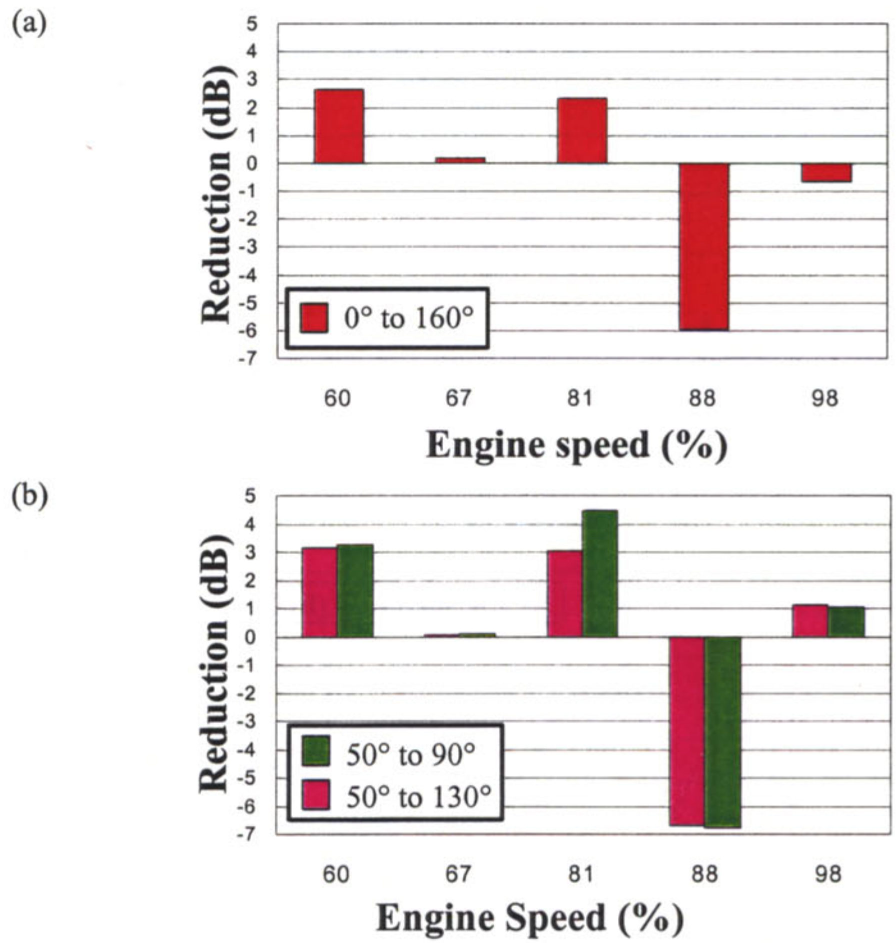


Figure 4.1: BPF power reduction with Array 2, (a) total power reduction, (b) power reduction over sectors.

Figure 4.1 also shows that at the higher engine speed of 88%, there is considerable increase in the power radiated at the BPF tone with HQ Array 2. This increase in noise was believed to be primarily due to the array interacting with the rotor. It should be noted that, when Array 1 was implemented (and with both arrays together) the radiation at the BPF tone increased, even at some of the lower engine speeds. This is believed to be due to the fact that since Array 1 was in such close proximity to the fan, that even at low engine speeds the interaction with the fan resulted in BPF tone level increase. Array 2 was far enough away from the fan that at lower engine speeds the interaction effects were not significant. This detrimental interaction effect is addressed further in later sections.

Figure 4.2(a) and (b) contain plots of the sound pressure level (SPL) directivity at the BPF tone for engine speeds of 60% (BPF = 2288 Hz) and 81% (BPF=3088 Hz) for all four cases tested, i.e., hard wall, Array 2 only, Array 1 only, and both arrays together. It is clear in these plots that the only configuration resulting in significant reduction is Array 2, which achieved a power attenuation of 2.6 dB due to the 2nd tube resonance and a power attenuation of 2.3 dB due to the 3rd tube resonance.

(a)

(b)

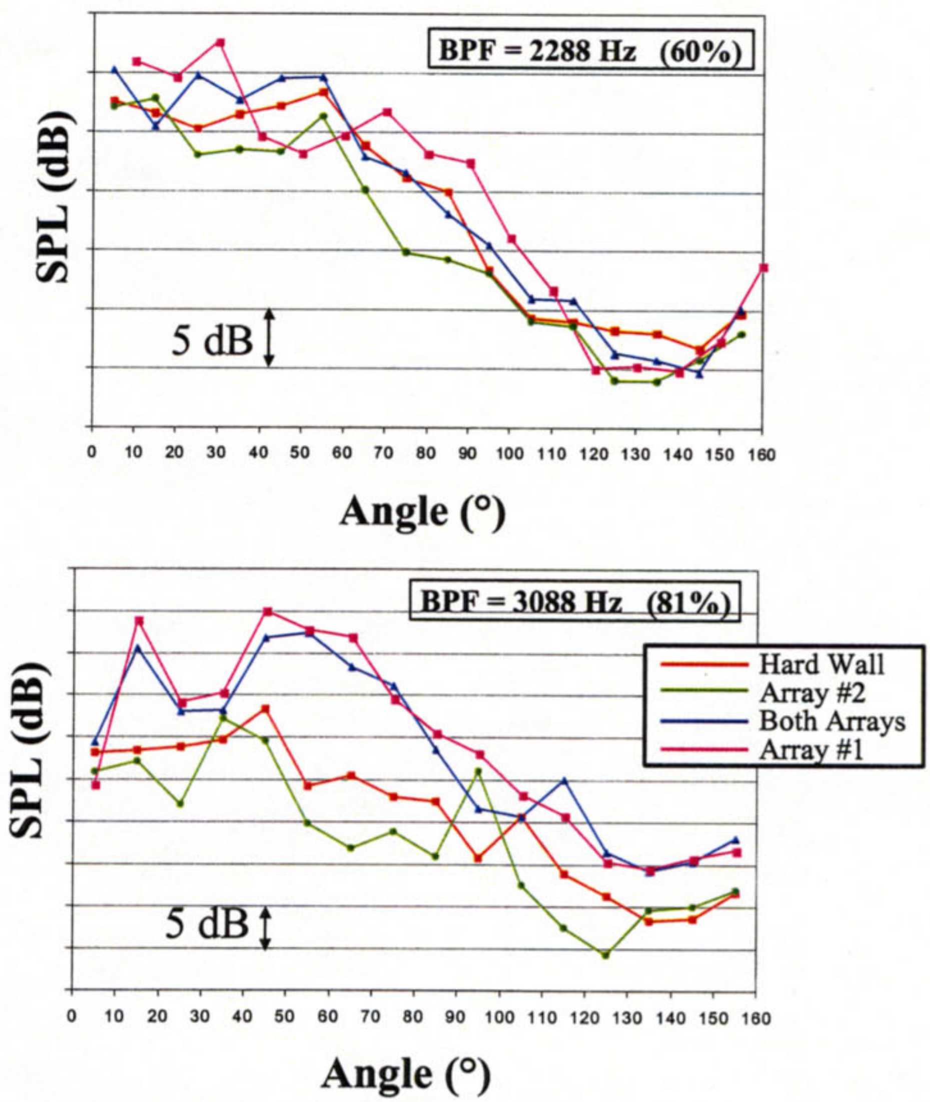


Figure 4.2: Far-field BPF directivity (a) 60% engine speed, (b) 81% engine speed.

4.1.2 Inlet modal power results at the BPF tone

The modal inlet measurements were made by NASA Langley researchers and provided to Virginia Tech [7]. The NASA spool piece shown in figure 3.5 was instrumented with an array of microphones and placed upstream of the HQ-arrays. Figure 4.3(a) and (b) show the inlet modal power of each cut-on mode at the BPF of 2288 Hz (60%) for the hard wall case and the case with Array 2, respectively. In this figure, the circumferential and radial order of the modes are defined by m and μ, respectively. The overall power reduction as computed using the modal data was 3.5 dB as compared to 2.6 dB calculated with the far-field data. The reduction of many of the modes with Array 2 is evident in the plots. Even more striking is the large number of modes with significant modal content for the hard-wall case. Clearly more dominant modes were measured than simply the predicted m=-8, 2 and 12. These data show the complexity of the sound field in the inlet of an actual running turbofan engine.

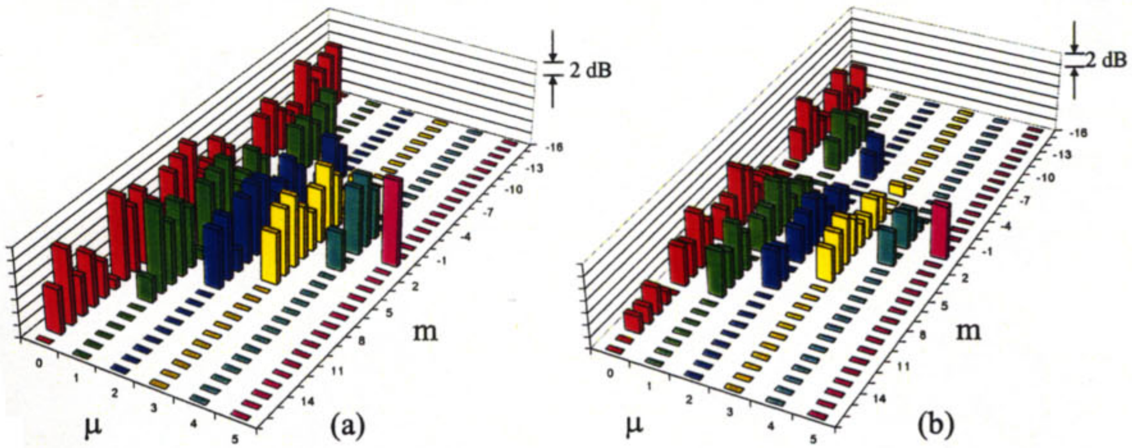


Figure 4.3: Inlet mode BPF measured power levels (a) hard wall, (b) Array 2.

The power reduction of each mode at BPF due to Array 1 alone and Array 2 alone is shown in the plots of Figure 4.4(a) and (b) respectively for the 60% engine speed. In these plots, blue means that the power was increased with the HQ tubes, and red means that the power was reduced. In Figure 4.4(a) for Array 2 only, most of the modes show reduction, with some increase in the m=-4 modes. This should be contrasted to the mode reductions in Figure 4.4(b) that show significant increase in modal powers due to Array 1 in many m-orders. The most significant "spillover", or mode increase, appears in the m=-5 modes which is clearly related to the interaction between the 22 fan blades and the 27 tubes in the array. The spillover effect is very evident for Array 1 most probably because of its proximity to the fan, i.e. strong interaction noise mechanism exists between the HQ-array and the fan. There are other modes showing reduction with Array 1, in particular for m=-1 and m=±15. Figure 4.5(a) and (b) shows a similar comparison between the modal power reductions due to Array 2 and the modal power reduction with both arrays together, respectively. It is shown that when the two arrays are combined, the attenuation effects of Array 2 help to compensate for much of the spillover due to Array

1, resulting in better overall mode reduction that with Array 1 alone. However, the strong spillover in the $m=\pm5$ modes due to Array 1 are still evident with both arrays.

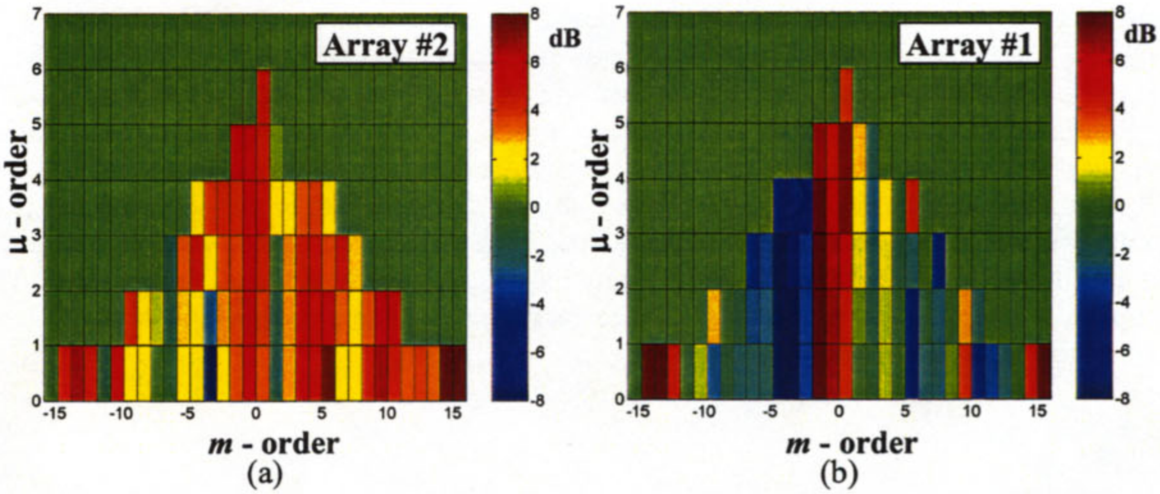


Figure 4.4: Inlet mode BPF measured power level reduction at 60% engine speed (a) Array 2, (b) Array 1.

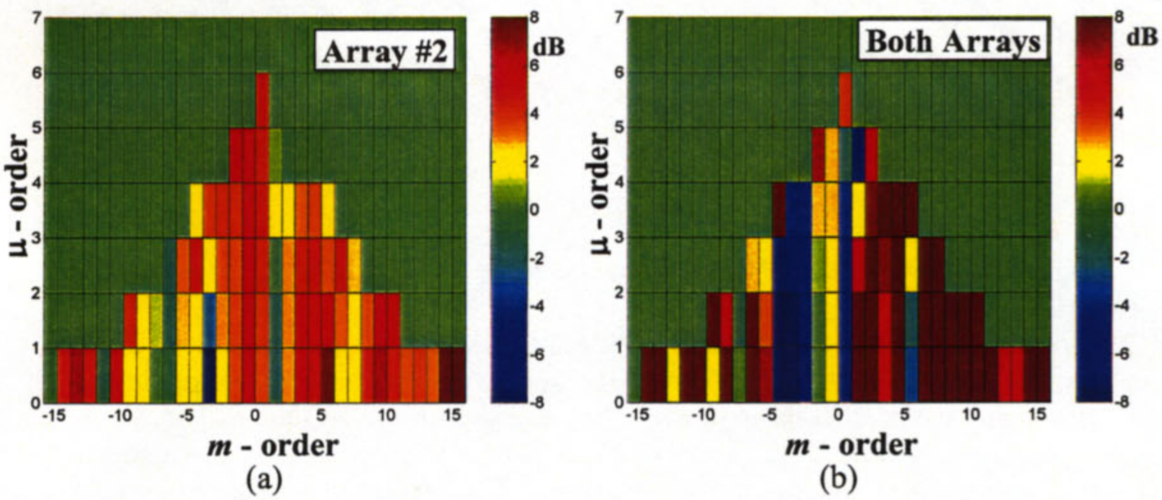


Figure 4.5: Inlet mode BPF measured power level reduction at 60% engine speed (a) Array 2, (b) both arrays.

Figure 4.6 shows a bar-plot of the total modal power in each m-order mode (summed over the radial modes) for Array 2 alone and Array 1 alone. In this figure, positive dB values mean reduction and negative values are an increase. In this plot, the increased m-orders in the vicinity of the m=5 modes are even more evident with Array 1. Good reduction at almost all the modes is obtained with Array 2.

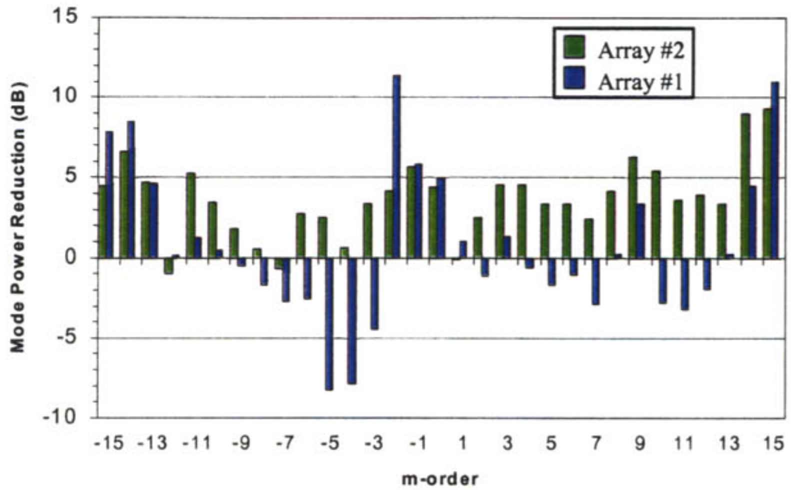


Figure 4.6: Inlet *m*-order mode total BPF measured power level reduction at 60% engine speed.

4.2. BROADBAND RESULTS

The HQ systems have also been shown previously to provide significant reduction of the broadband noise content radiated from turbofan engine inlets [1,2]. The A-weighted broadband power spectra for the hard wall, Array 2 and both arrays are shown in Figure 4.7 for an engine speed of 67%. These results show that broadband power reduction is obtained near 1000 Hz, 2100 Hz, and 3200 Hz, which correspond to frequencies near the 1st, 2nd, and 3rd resonances of the HQ tubes. Never before had reduction been observed at the first three resonances of the tubes. At this lower engine speed, it is also clear that the broadband reduction achieved with both arrays exceeds the reduction with Array 2 alone. Broadband power reductions in excess of 3 dB were obtained at some frequencies with both arrays. It is a common practice to present the noise spectrum in 1/3 octave bands for engine noise evaluation purposes. Thus, the A-weigthed power spectrum for the four configuration tested at 67% is presented in 1/3 octave band levels in Figure 4.8. Significant reductions of the one-third octave band levels are obtained in most of the bands, except for the 2500 Hz band which contains the BPF tone. In this band, Array 1 resulted in an increase in the noise due to the detrimental interaction effects with the fan mentioned in previous results.

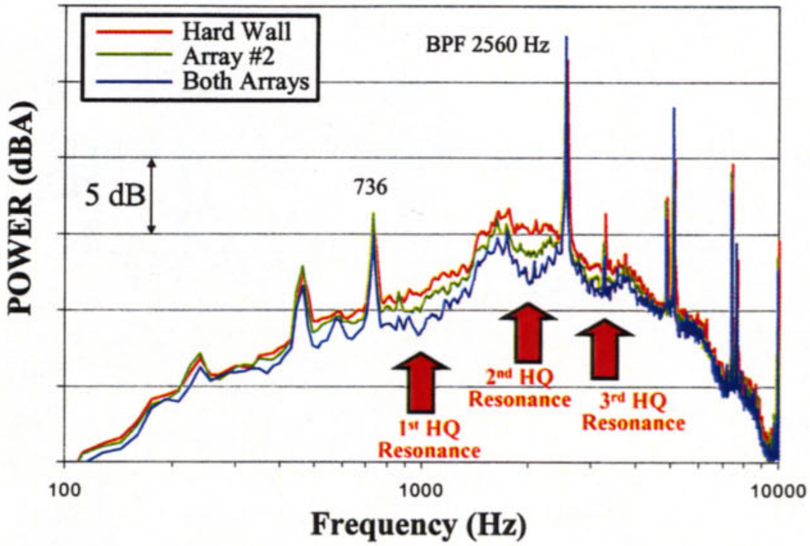


Figure 4.7: A-weighted power spectra 67% engine speed.

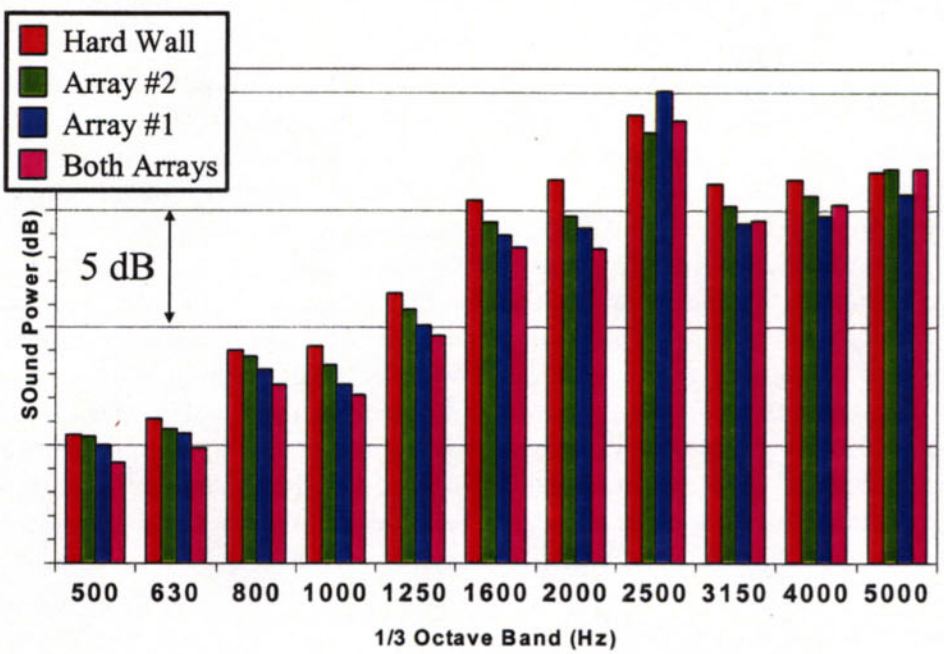


Figure 4.8: A-weighted one-third octave band power levels 67% engine speed.

The A-weighted power spectra at 81% engine speed are shown in Figure 4.9 for the hard wall and Array 2 cases, and these two spectra are shown together with the spectra for both arrays together in Figure 4.10. Figure 4.9 shows good reduction with Array 2 at most of the frequencies on the range, including reduction at the BPF and second BPF. Array 2 is also shown to provide significant power reduction (greater than 7 dB) of the tone generated at 1888 Hz which is a "combination tone" (See next section). It is seen in Figure 4.10, the addition of Array 1 leads to a considerable increase in the reduction of the power at around 2000 Hz where the broadband components dominates. In addition, even more reduction of the 1888 Hz tone is achieved, i.e. over 10 dB below the hard wall level.

Also evident in Figure 4.10, however, is the considerable increase in the high-frequency tone noise above 3000 Hz due to the addition of Array 1 closest to the fan. This additional increase is prevalent at the higher engine speeds with Array 1 at 81%, 88%, and 98%, and only present with Array 2 (furthest from the fan) at 88% and 98%. Thus even at lower speeds, the HQ-arrays were responsible for face distortion that resulted in noise increase, i.e. 81% and higher power settings for Array 1 and for power settings 88% and higher for Array 2. Though this problem was not further investigated, it was speculated that a potential cause for the flow distortion is due to the large screen holes (see figure 3.3) that resulted in flow separation, i.e. wakes. This detrimental effect can be greatly reduced with a smaller screen construction, like the one that was designed.

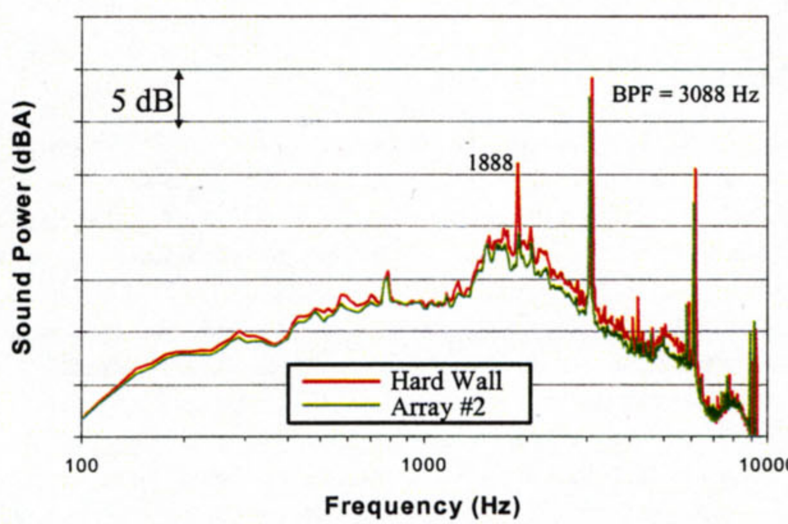


Figure 4.9: A-weighted power spectra 81% engine speed.

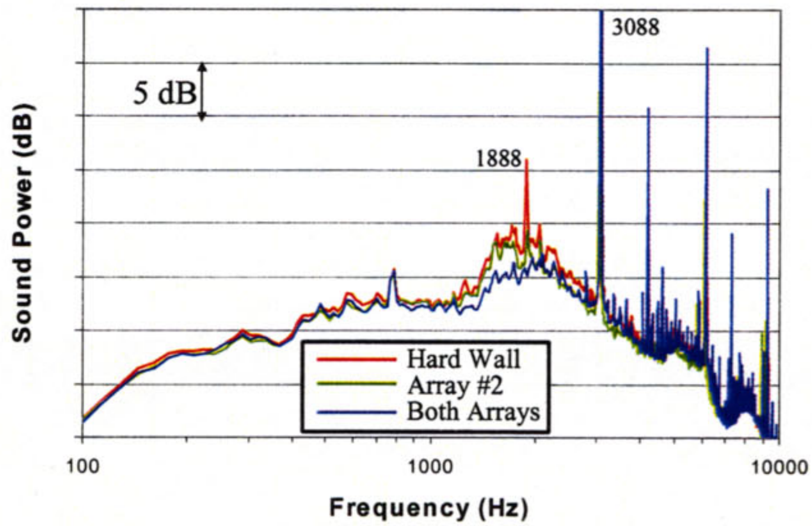


Figure 4.10: A-weighted power spectra 81% engine speed.

4.3. COMBINATION TONE RESULTS

The fan of the TFE731-60 engine becomes transonic at 81% power setting. At transonic condition, the fan generates "combination" or "buzz-saw" tones, which are generated over the frequency range from about 800 to 3000 Hz. In these experiments, the combination tones were most prevalent at the 88% and 98% test speeds. Figure 4.10 shows a single combination tone at 81 % power setting. Figure 4.11 shows the A-weighted power spectra at 88% engine speed for the hard wall, Array 2, and both arrays together. In this figure, there are five significant combination tones. Considerable reduction of all the combination tones is evident with Array 2 only, and even more reduction is obtained with both arrays. It is very interesting to note that the HQ-arrays have been very effective at controlling all combination tones independently of their frequency. Thus, it seems that the HQ-concept can control these combination tones even if they are not near a tube's resonance. In practice, these combination tones are attenuated using a high-depth core liner placed near the fan. The ability of the HQ system to provide such an extreme amount of reduction at these tones is of considerable importance. This is because the HQ technology offers the option to remove the high-depth core liner leaving additional surface to be used by conventional liner treatment.

The results in terms of 1/3 octave band levels for the 88% power setting for all cases tested are shown in Figure 4.12. The reduction in the 1600 Hz band (the band in which most of the combination tones reside) exceeds 7 dB with both arrays. Once again the increase of power in the 3150, 4000, and 5000 Hz bands is due to the fan face distortions generated by both arrays.

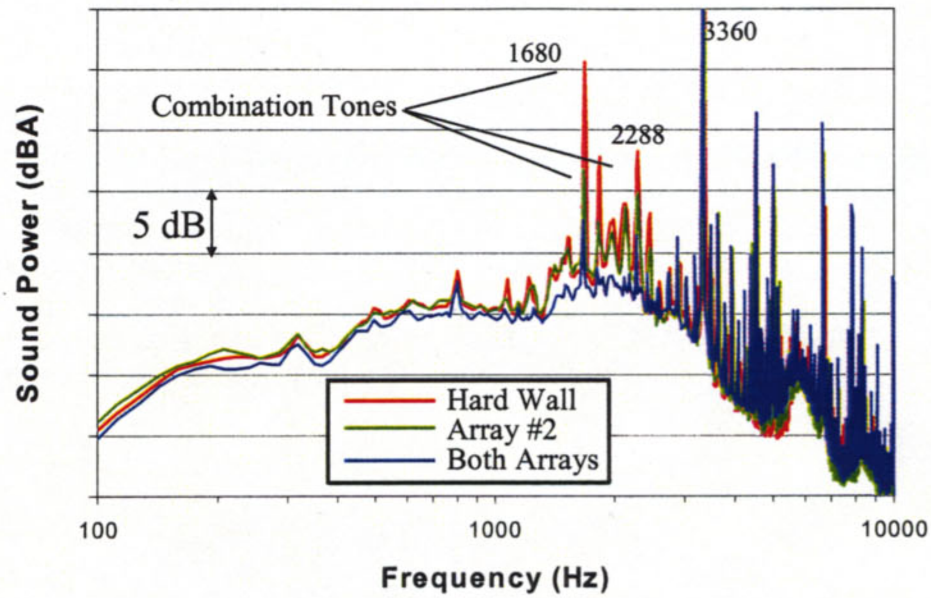


Figure 4.11: A-weighted power spectra 88% engine speed.

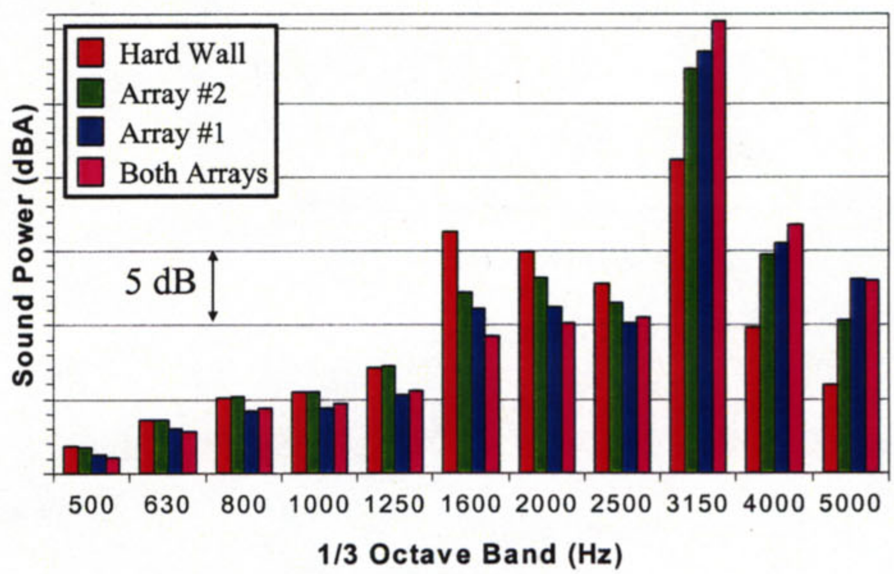


Figure 4.12: A-weighted one-third octave band power levels 88% engine speed.

4.4. OVERALL RESULTS

In order to illustrate the overall performance of the HQ-system, the 1/3 octave band level power reductions for all engine power settings are presented in Figure 4.13. Figure 4.13(a) shows the 1/3 octave band power reduction with Array 2 and Figure 4.13(b) shows a similar plot for both arrays. Here, the overall picture in terms of reduction and fan distortion can be seen. Using Array 2 (Figure 4.13(a)), reduction is generally observed at the lower engine speeds at the first three HQ resonances. As the engine speed increases, most of the reduction occurs in the 2000 Hz band and at higher speeds, a large amount of reduction occurs just below 2000 Hz, due to the HQ effect on the combination tones, as pointed out in the figure. Also shown in the figure is the large area of increased noise at the higher frequencies at the higher engine speeds due to the fan distortion effect. Using both arrays (Figure 4.13(b)) more significant reductions take place below 2000 Hz, and again the region of reduction due to the combination tone effects is shown in the figure. A larger region of fan distortion, beginning at a lower engine speed is also evident with both arrays, due to the proximity of Array 1 to the fan.

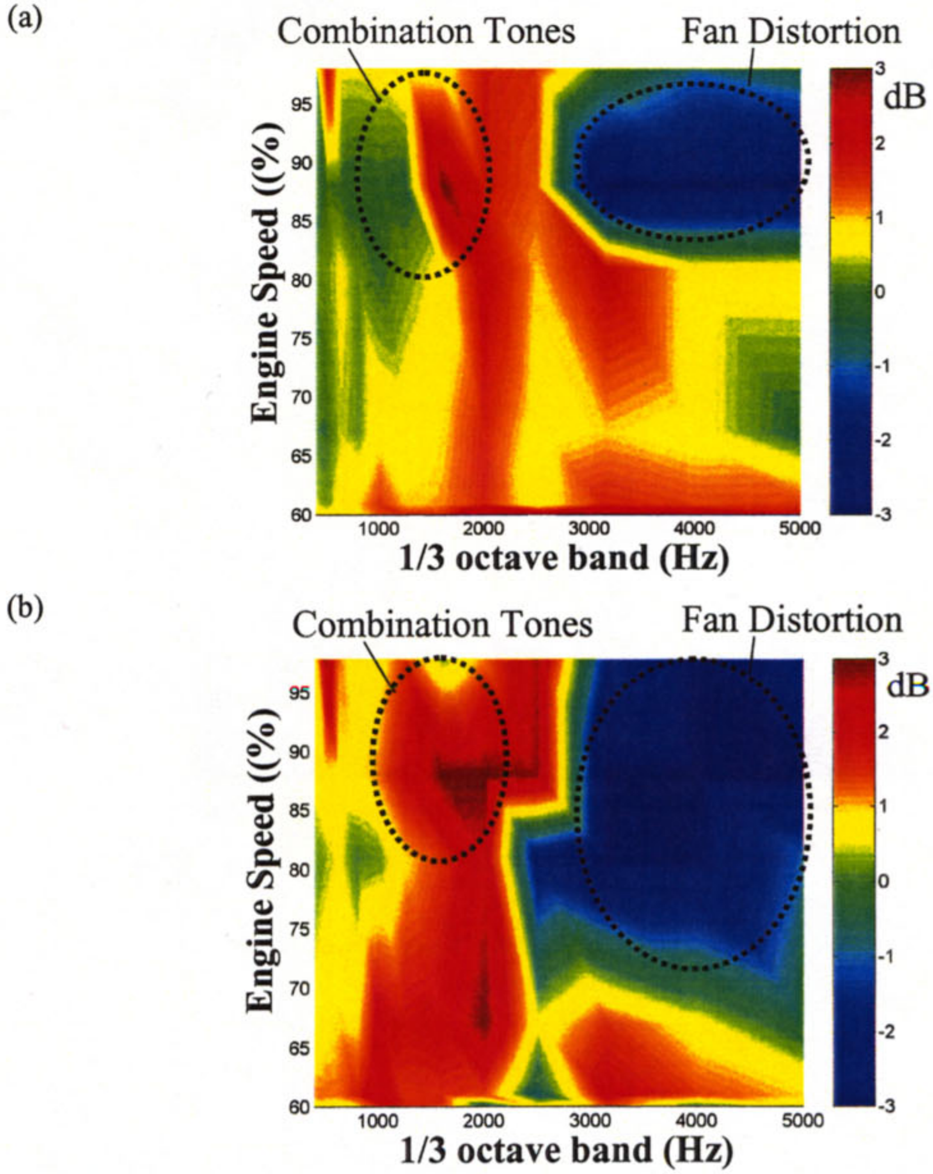


Figure 4.13: A-weighted 1/3 octave band power reductions by engine speed (a) Array 2, (b) both arrays.

5. CONCLUSIONS

The results from these experiments show the potential of the HQ technique for attenuating radiated inlet noise from the TFE731-60 engine. Both broadband and tonal reductions were observed when the HQ array was placed at some distance from the fan. Furthermore, reduction of "combination", or "buzz-saw" tones, i.e., additional tones radiated from the inlet when the fan tip speed goes supersonic, were observed with the HQ system. The following are the main conclusions obtained from the research performed in this work:

1) The potential of the HQ concept has been demonstrated on a full scale production engine with very encouraging results, i.e., with Honeywell calculations, array #2 yielding a reduction of ~ 2.0 dB EPNLdB at 81% speed.
2) Good BPF tone power reduction was obtained: ~ 2.6 dB at 60% due to 2nd tube resonance and ~ 2.3 dB at 81% due to 3rd tube resonance.
3) The HQ tube concept was shown to be effective at reducing the broadband noise near the first THREE resonant frequencies of the tubes.
4) The HQ tubes were shown to be very effective at reducing "combination tone" noise, e.g. power reduction of up to 12.1 dB.
5) Fan distortion and increase in noise was observed at higher engine speeds, in particular for the array near the fan.
6) A design strategy has been established and shown to be effective.

In general, the application of HQ tubes to the problem of turbofan jet engine noise has been demonstrated to be an extremely effective and viable strategy. The HQ tubes would not necessarily require a significant amount of space on the engine inlet, and are therefore expected to be able to be designed concurrently with a passive liner. It is anticipated that the HQ concept could be used for attenuation of the low-frequency broadband noise, combination tones and BPF tones, whereas the passive liner could be designed to attenuate the higher-frequency noise where it is most effective. These results on a full-scale production turbofan engine with actual noise-generation mechanisms further prove that the HQ technique has considerable potential for application in industry.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

A number of "research issues" requiring further investigation have also surfaced from this work. Probably the most critical issue is to investigate the high frequency noise increase due to fan distortion. Some of the suggested possible causes of this problem are flow separation due to the screen used (i.e. large orifices), induced flow in the tubes due to pressure gradient, and rotor potential flow field affecting the tubes.

Another important issue is to investigate the combined effect of HQ tubes with the passive liner as well as to establish a design approach for the HQ system in conjunction with passive liners or other noise control technologies.

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13. ABSTRACT ***(Maximum 200 words)***
This report summarizes the key results obtained by the Vibration and Acoustics Laboratories at Virginia Tech over the period from January 1999 to December 2000 on the project "Investigation of an Adaptive Herschel-Quincke Tube Concept for the Reduction of Tonal and Broadband Noise from Turbofan Engines", funded by NASA Langley Research Center. The Herschel-Quincke (HQ) tube concept is a developing technique the consists of circumferential arrays of tubes around the duct. A fixed array of tubes is installed on the inlet duct of the Honeywell TFE731-60 engine. Two array designs are incorporated into the inlet treatment, each designed for a different circumferential mode order which is expected to be cut on in the duct. Far field and in-duct noise measurement data are presented which demonstrate the effectiveness of the HQ concept for array 1, array 2, and both operating simultaneously.

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